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# Bennet's Doubler With Double Capacitive TENG for Kinetic Energy Harvesting

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**Abstract**— Unstable charge pumps used as rectifier circuits for triboelectric generators, like the Bennet's doubler, have been proven to drastically improve the harvested power compared to traditional diode bridges, at the cost of longer starting time. In this work, we propose for the first time a kinetic energy harvesting system based on the Bennet's doubler, polarizing two triboelectric transducers with antiphase capacitance variations, instead of just one triboelectric transducer. We show that this configuration reduces the time needed to reach the circuit's unstable regime compared to its single-transducer counterpart. Consequently, the harvested power is increased.

**Keywords**— Triboelectric nanogenerator, Bennet doubler, charge-pumps, asymmetric variable capacitors

## I. INTRODUCTION

Powering up Internet of Things (IoT) devices is one of today's challenges. One mean to tackle this challenge is by *energy harvesting*: converting part of the energy present in the device's environment into electrical energy, in order to supply the device with it. Electrostatic kinetic energy harvesters (e-KEHs) are a type of system performing this conversion, from kinetic to electrical energy. They are based on electrostatic transducers, which convert the work of an external mechanical input acting on their terminals, into energy in the electrostatic field between them. In order to work, these transducers require some initial biasing to bootstrap the energy conversion process. This initial biasing is usually provided either by an external power source, or by an electret layer deposited on the surface of at least one of the electrodes of the transducer. With MEMS (microelectromechanical systems) electrostatic transducers, the electret layer is typically obtained during fabrication by corona discharge or soft x-ray [1]. Triboelectric transducers (also called TENGs, for triboelectric nanogenerators) [2] are another type of electrostatic transducers. Their electret layer is charged by contact electrification, upon mechanical contact between the transducer's terminals subjected to a mechanical input.

The polarization dynamics of the electrostatic transducer while it is subjected to an external mechanical forcing determine the energy converted by the e-KEH [3]. Any e-KEH comprises a conditioning circuit, whose role is precisely to set these dynamics, as well as to make the converted energy available to the load in suitable form (e.g., at a regulated low voltage value). Unstable charge-pumps like the Bennet's doubler are a type of conditioning circuit. They allow to

continuously increase the average biasing voltage of the transducer during its operation, and hence the converted power. The limits on power conversion are then set by effects such as components breakdown or electromechanical coupling, while other conditioning circuits (such as the classical diode bridges) inherently set a limit on the converted power due to their transducer polarization dynamics.

The Bennet's doubler and other unstable charge-pumps have been used for the electrical conditioning of MEMS resonant single variable capacitors such as in [4], [5]. The work [6] reports on the first experiments featuring a TENG using unstable charge-pumps as conditioning circuits. It shows a large improvement in the harvested power compared to classical diode bridges conditioning circuits. The Bennet's doubler has also been studied as a conditioning circuit of dual-transducers with antiphase capacitance variations. Notably, De Queiroz first studied the circuit with two antiphase variable capacitors of trapezoidal variation waveforms, and with an initial biasing provided by an external source [7]. The same circuit was used with a MEMS electrostatic transducer in [8]. In [9], Dragunov *et al.* report on a detailed study of the transient regime of this circuit, when one of the electrodes has a permanent electret (or triboelectric) charging.

In this work, we describe the operation of the Bennet's doubler used as the conditioning circuit of two TENGs with antiphase capacitance variations. We then present experimental results comparing single and dual antiphase TENGs, both polarized by the Bennet's doubler. The results show that the dual-transducer system reaches the unstable energy conversion mode of the Bennet's doubler faster than a comparable single-transducer system. This implies a larger average converted power.

## II. SYSTEM DESCRIPTION

### A. TENG description

In order to build the required initial bias, TENGs take advantage of the triboelectric effect to accumulate charges in the dielectric material separating their electrodes, when they are in contact. The trapped charges create a surface voltage. This voltage is amplified by electrostatic induction upon separation of the transducer's electrodes, due to the external mechanical forcing.

TENGs can show lateral, transverse, or rotational relative motion of their electrodes. This categorises them as sliding,

gap-closing, or rotating transducers. In general, gap closing capacitive TENGs constitute of one fixed electrode covered by charge trapping material, while the other electrode with only a conductive material is mobile (Fig. 2).

By adding another fixed electrode, a 3-ports TENG with two antiphase variable capacitors is obtained. Such a device consists of three electrodes A, B and C, as depicted in Fig. 2. Between A and B is the capacitor  $C_{t+}$ , and between B and C, is the capacitor  $C_{t-}$ . The electrodes A and C are fixed, and the electrode B is left mobile. Adding a triboelectric layer, in this case polytetrafluoroethylene (PTFE), to the surfaces of each fixed electrodes (A and C) transforms the two variable capacitors into two TENGs.

The electrode B is mechanically actuated by a feedback linear motor set to track a sinusoidal displacement. The tracked average position and displacement amplitude are such that the transducer's electrodes A/B and B/C are in contact for a fraction of the input period. The two corresponding variable capacitors vary in anti-phase. In particular, they reach opposite extrema of their capacitance value at the same time (one reaches it maximum when the other reaches its minimum, and *vice versa*).

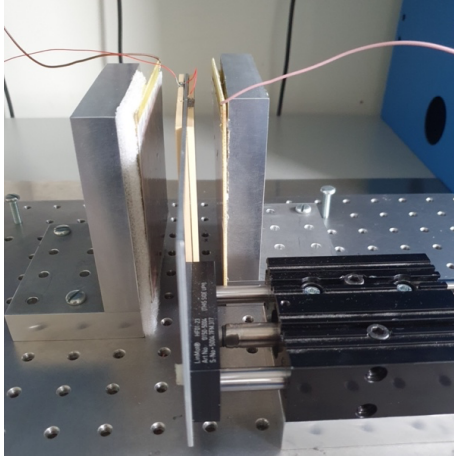


Fig. 1. An image of the 3-port TENG used for experiments, where fixed plates are A and C and electrode B is set in motion using a linear motor.

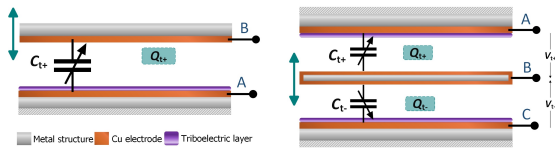


Fig. 2. Schematic representation of a 2-port TENG with its capacitance  $C_{t+}$  (left) and a 3-port TENG with corresponding capacitances  $C_{t+}$  and  $C_{t-}$  (right).

### B. Circuit description

Stable and unstable charge pumps are widely used as conditioning circuits for TENGs. Stable charge-pumps reach saturation within a few cycles of operation, defined as the variation of the transducer capacitance from one local maxima (or minima) to the next maxima (or minima). At the saturation

point, the energy conversion stops. On the other hand, unstable charge-pumps can show steady-state operation regimes in which the converted power is not bounded and increases exponentially, only to be limited by effects such as electrical component breakdown.

The simplest circuit from unstable charge pump family is the Bennet's doubler, whose topology is depicted in Fig. 3 left. In this figure, the Bennet's doubler is used to bias a (single) TENG, modelled as a variable capacitor  $C_{t+}$  in series with a voltage source  $V_{te+}$ . The latter represents the effect of the triboelectric charging of the dielectric layer. The circuit is composed of 3 diodes  $D_{1,2,3}$ , a reference capacitor  $C_{ref}$ , and an output capacitor  $C_{st}$  used for charge accumulation.

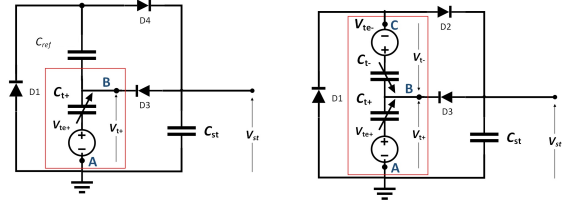


Fig. 3. Bennet's charge doubler circuit with 2-port TENG presented through its electrical equivalent of a variable capacitor and a DC voltage source (left). A new take on Bennet's charge doubler circuit with 3-port TENG, double capacitor transducer (right).

The Bennet's doubler depicted in Fig. 3 on the right is used as the conditioning circuit of a dual-transducer TENG with a common electrode, corresponding to the device described in Sec. II-A above. The electrical equivalent of each e-KEH is a variable capacitor ( $C_{t+}$  and  $C_{t-}$ ) and a DC voltage source ( $V_{te+}$  and  $V_{te-}$ ) connected in series. The voltages  $V_{te+}$  and  $V_{te-}$  are related to the surface voltages of the electret layers.

## III. RESULTS

### A. Analytical results

The dynamics of the dual-transducer TENG + Bennet doubler across one cycle of operation can be fully characterized by the charge-voltage (QV) diagram of the transducer. In case of a double variable TENG, the QV diagram consists of two separate curves in the QV plane. As shown in Fig. 5, the QV cycle (corresponding to one mechanical cycle of the transducer) has 5 segments resulting in an initial charge increase between two successive cycles for both transducers. Fig. 4 and Fig. 5 show the circuit and QV evolution respectively.

Both capacitors  $C_{t+}$  and  $C_{t-}$  start at point A, at opposite capacitance extremes  $C_{t+} = C_{max}$  and  $C_{t-} = C_{min}$ , with the same voltage  $V_{t+|A}$ . All diodes in the circuit are off, and the transducer is cut off from the rest of it. As an external mechanical force is applied, the mobile electrode is displaced and  $C_{t+}$  decreases while  $C_{t-}$  increases, resulting in voltage variations across the two capacitors.

This leads to point B' at which the diode  $D_2$  turns on and all three capacitors of the circuit are now in series. At this moment,  $C_{t+}$  releases the charges to the rest of the circuit, and  $C_{t-}$  and  $C_{st}$  accept them. At point D', when the TENG's capacitors have reached opposite capacitance extremes, the diode  $D_2$  stops conducting and the TENGs are cut from the circuit again.

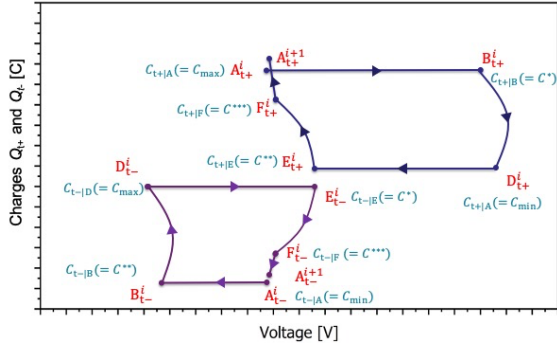


Fig. 4. A drawing of the flow the two QV cycles generated by two transducer's capacitors in  $i^{\text{th}}$  mechanical cycle of operation of the TENG and circuit.

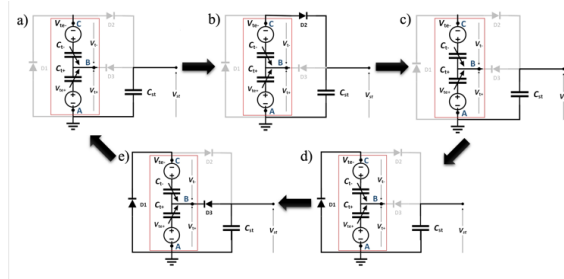


Fig. 5. A flowchart of the evolution of Bennet's charge doubler circuit with double capacitive TENG consisting of five active changes corresponding to one of the points on the QV cycle.

With the mobile electrode continuously being displaced, the QV cycles evolve from point  $D^i$  to  $E^i$  at which the two capacitors have the same potential and diode  $D_1$  starts conducting, transforming the circuit into a parallel connection between the two TENG's capacitors. At this point, charges are released from  $C_t^-$  and are accumulated in  $C_{t+}$  until the two parts of this capacitive transducer reach the new potential level labeled as point  $F^i$ , at which the additional diode  $D_3$  turns on. At point  $F^i$ , the three capacitors are connected in parallel. In the final phase of one evolution of the QV cycle, capacitors are revolving back to their initial values, while the final charge exchange and voltage variation occurs, resulting in another equi-potential point  $A^{i+1}$  at which all diodes are off. If point  $A^{i+1}$  is closely observed, it can be seen that from the  $i^{\text{th}}$  to the  $(i+1)^{\text{st}}$  cycle, there is an increase in voltage and charge which is applicable to any two cycles taken in the mechanical evolution of the transducer. This fulfills the core criteria of Bennet's charge doubler, which is an exponential increase.

Comparing the analysis of a single TENG to a double one, it is concluded that the presence of a second variable capacitor complexifies the analysis as they are codependent, calling for parametric  $Q(t)$  and  $V(t)$  analysis computed in parallel for both  $C_{t+}$  and  $C_{t-}$ .

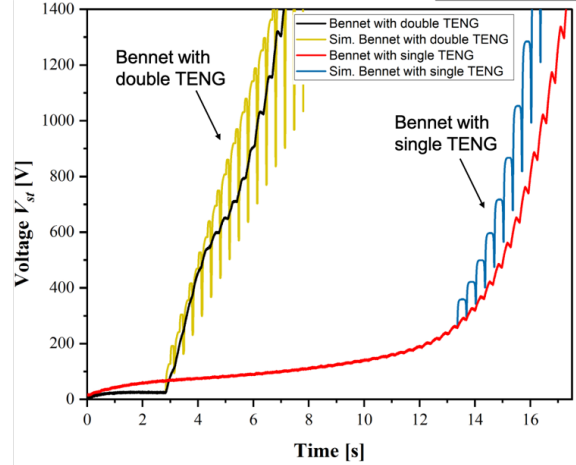


Fig. 6. Performance comparison of the experimental results of Bennet's doubler with single and double TENG and their simulation results.

## B. Experimental and simulation results

To corroborate the analysis, we performed experiments with the physical device shown in Fig. 1. It has a  $100 \mu\text{m}$ -thick PTFE material as a triboelectric layer and the plates overlapping area is  $9 \times 9 \text{ cm}^2$ , with an initial gap of 5 mm. Using the dynamic capacitance measurement method presented in [10], the two asymmetric variable capacitors were recorded with  $C_{\text{max}} = 675 \text{ pF}$  and  $C_{\text{min}} = 45 \text{ pF}$ , corresponding to a ratio  $\eta = C_{\text{max}} / C_{\text{min}} = 15$ . The circuit is completed with high-voltage diodes and capacitors,  $C_{\text{ref}}$  and  $C_{\text{st}}$  being both equal to 1 nF.

To substantiate the effectiveness of a Bennet's doubler, we can take a look at its output. As mentioned above, for the Bennet's doubler to operate with an exponential increase, initial conditions need to be met. Indeed, as shown in Fig. 6, a transient stage is present at the beginning of the conversion process in the form of a first increase of  $V_{\text{st}}$  before reaching a plateau. The Bennet doubler with the double TENG completes the transient stage within 3 seconds and then has a quick and sharp increase in output voltage. Nevertheless, the Bennet doubler with the single TENG can surpass the transient stage and operate as a charge multiplier in approximately 12 seconds, with a mild but yet very clear exponential increase.

A set of Spice simulations have also been conducted. Initial conditions are such that no transient period is simulated. From Fig. 6, we can see that both experimental and simulation curves follow the same trend. While Bennet with the single TENG exercises a slightly milder exponential increase compared to the simulated circuit, Bennet with the double TENG has a good match with the simulation results.

## IV. CONCLUSION

From measurements and simulations done in the framework of this paper comparing single and double variable TENG with a Bennet's doubler, it can be concluded that the double variable capacitor configuration is noticeably more efficient in terms of speed and harvested energy per cycle. The significant difference in efficiency between both

configurations can be seen by analysing the harvested energy of one of the mechanical cycles of the TENG as there is a higher voltage variation per cycle for double than single TENG. This places Bennet's doubler with double capacitive TENG among circuits with high-efficiency rate and a wide variety of applications.

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